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Bipolarity in structure and dynamics of the Earth's mantle[1])

By Nazario Pavoni[2])

ABSTRACT

Plate reconstructions for the Mesozoic and Cenozoic reveal a simultaneous breakup of the older lithosphere and subsequent, large-scale diverging plate motions in both the Pacific and Eurafrican hemispheres. In the Pacific hemisphere, which is centered at 170° W/0° N (pole P), Mesozoic and Cenozoic diverging movements of plates away from the central Pacific region toward the margins of the Pacific are documented by the evolution of the system of oceanic ridges. The Pacific plate was formed in the center of the Izanagi-Farallon-Phoenix triple junction about 175 Ma ago, and grew from a small plate to its present large, circular size. The magnetic remanent inclination, composition and microfossil content of Jurassic rocks recovered 1990 during the ODP Leg 129 in the Pigafetta basin prove that the Pacific plate was formed at equatorial paleolatitudes. During the growth of the plate the center of the Pacific plate remained in equatorial latitudes; i.e., the growth of the Pacific plate was more or less symmetrical with respect to the equator. Large-scale diverging plate motions in the Pacific hemisphere during the last 180 Ma were actually directed away from a common "spreading center" on the equator. In the anti-Pacific hemisphere, which is centered in Africa at 10° E/0° N (pole A), Mesozoic and Cenozoic diverging movements of plates away from Africa are demonstrated by the breakup of Gondwana and the growth of the African plate. The simultaneous, large-scale, diverging plate motions in the Pacific and Eurasian hemispheres during the last 180 Ma reveal a fundamental hemispherical symmetry or bipolarity of global tectonic processes. The bipolarity is defined by the two spreading centers P and A in the central Pacific and in Africa.

Active mantle drag force is considered to be the dominant plate driving force. Active oceanic ridges represent weak zones of the lithosphere along which the neighbouring plates are torn apart. Intrusion of mantle material is a passive consequence of the separation of plates. Unidirectional, horizontal flow is assumed to exist in the mantle beneath the active oceanic ridges. In order to explain the lithospheric evolution in the Pacific and anti-Pacific hemispheres, a model of bicellular convection in the mantle, has been proposed, consisting of two toruslike convection cells, with ascending flow under the central Pacific and African plates, and converging and descending flow at 70° to 90° distance from both pole P and pole A. The bicellular convection governs the large-scale patterns of plate motions. Whereas the oceanic lithosphere is directly taking part in the circulation of mantle material, the continental lithosphere mainly remains at the surface of the Earth. The geotectonic bipolarity model provides a simple explanation of geotectonic cycles.

Recent geophysical investigations show that the same, fundamental Pacific/anti-Pacific bipolarity is evident in the degree 2 distribution of lateral heterogeneities of seismic velocity and density in the lower mantle, as well as in the form of the residual geoid. This points to a common origin of the anomalies and the bipolarity. Reduced seismic velocities, indicating less dense and relatively hot material, observed in the lower mantle beneath the central Pacific plate and beneath the African plate, are in good agreement with the bicellular convection proposed on geotectonic considerations. The existence of a fundamental geotectonic bipolarity is, thus, founded on independent, geological and geophysical, evidence.

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ZUSAMMENFASSUNG

Geologische Beobachtungen im zirkum-pazifischen Gebirgsgürtel sowie Untersuchungen über die Entwicklung des Systems der aktiven ozeanischen Rücken im Gebiet des Pazifik in den letzten 180 Mio. Jahren lassen übereinstimmend eine Divergenz der Bewegungen der Lithosphärenplatten vom Zentrum zu den Rändern des Pazifik hin erkennen: Relativ zur zentral gelegenen Pazifischen Platte bewegten sich die Izanagi Platte und die Kula Platte gegen NW und N und wurden unter Asien und Alaska subduziert; die Farallon Platte bewegte sich gegen NE und E und wurde unter Nord- und Südamerika subduziert; die Phoenix Platte bewegte sich gegen SE und S und wurde unter Südamerika und der Antarktis subduziert. Gleichzeitig vergrösserte sich die Pazifische Platte bis zu ihrer heutigen Ausdehnung. Ihr Zentrum P liegt bei 170°W/0°N auf dem Äquator. Die Pazifische Platte entstand vor etwa 175 Mio. Jahren als kleine Platte im Zentrum der Izanagi-Farallon-Phoenix Triplejunction in der Nähe des Äquators, wie aus den Bohrergebnissen des ODP Leg 129 im Pigafetta Becken geschlossen werden kann. Gleichzeitig mit den Plattenbewegungen im Gebiet des Pazifik hat sich auch in der dem Pazifik gegenüberliegenden eurafrikanischen Hemisphäre eine vergleichbare Aufspaltung der Lithosphäre abgespielt. Sie ist durch die Zerbrechung von Gondwana und die divergierende Drift der Kontinente relativ zu Afrika eindrücklich dokumentiert. Das Zentrum A der Afrikanischen Platte liegt bei 10°E/0°N. Aus der zeitlich parallel verlaufenden Entwicklungsgeschichte der Lithosphäre in der pazifischen und eurafrikanischen Hemisphäre kann auf eine fundamentale, hemisphärische Symmetrie oder Bipolarität globaler, tektonischer Vorgänge geschlossen werden. Die Bipolarität ist durch die beiden Pole P und A bestimmt.

Es wird angenommen, dass die Bewegungen der Lithosphäre im wesentlichen durch die Strömungen im Mantel verursacht werden. Als Modell zur Erzeugung der grossräumigen Plattenbewegungen wird ein bizellulares Strömungssystem im Erdmantel, bestehend aus zwei torusförmigen Konvektionszellen mit zylindrisch aufsteigender Strömung unter der zentralen Pazifischen Platte und unter Afrika, vorgeschlagen. Unter den aktiven ozeanischen Rücken wird im Mantel eine einseitig gerichtete, horizontale Strömung angenommen. Die Annahme einer unidirektionalen, horizontalen Strömung unter den aktiven ozeanischen Rücken ist eine Voraussetzung für die Konstruktion des bipolaren, geotektonischen Modells.

Geophysikalische Untersuchungen über laterale Heterogenitäten seismischer Geschwindigkeiten und Gesteinsdichten im unteren Mantel sowie über die Form des Residualgeoides lassen dieselbe fundamentale, pazifisch-afrikanische, hemisphärische Symmetrie erkennen wie sie aus der Evolution der Lithosphäre abgeleitet wurde. Dies deutet auf eine gemeinsame Ursache der Anomalien und der Bipolarität hin. Die Existenz einer fundamentalen, geotektonischen Bipolarität ist somit durch geologische und geophysikalische Beobachtungen eindrücklich belegt.

Introduction

It is the purpose of this paper to summarize a series of geological and geophysical observations which point to a fundamental hemispherical symmetry or bipolarity in global tectonic processes. The bipolarity is apparent, for example, in the similar and synchronous evolution of the lithosphere in the Pacific and Eurafrican hemispheres during the last 200 Ma, and in the conformity of seismic velocity and density heterogeneities in the mantle of these hemispheres.

The idea of a Pacific/anti-Pacific hemispherical symmetry in geotectonics arose in the early sixties as a result of investigations toward a synthesis of recent and late-Cenozoic crustal movements on a global scale (Pavoni 1962, 1969). The study was based on a systematic kinematic analysis of late-Cenozoic deformation of the young folded mountain belts, and showed the importance of strike-slip faulting in crustal deformation. Large-scale regularities were found in the pattern of orientation of maximum horizontal crustal shortening within the Eurasian and circum-Pacific orogenic belts. As a result, these belts were interpreted to represent a zone of intense crustal shearing and convergence between two large, expanding geotectonic units, the Pacific unit, centered in the central Pacific, and the Gondwana unit, centered in Africa (Fig. 1).

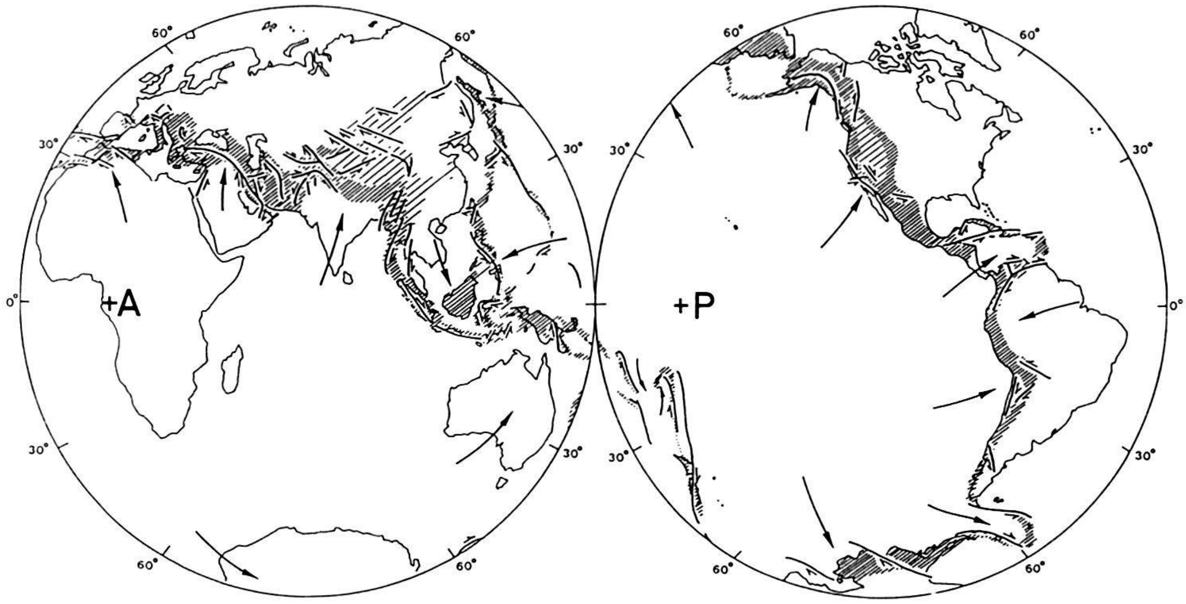

Fig. 1. Pattern of major strike-slip fault zones within the Eurasian and circum-Pacific orogenic belts (hatched area) after PAVONI (1962), and related large-scale, horizontal movements of the lithosphere (large arrows). The young orogenic belts represent a zone of convergence and shearing of the lithosphere located in between two major expanding geotectonic units, the Pacific unit (center P) and the Gondwana unit (center A).

The results of combined, geophysical and geological research in the oceanic regions in the late sixties and in the seventies, brought an additional and independent confirmation of the geotectonic bipolarity. The world-wide distribution of earthquakes associated with the active oceanic ridges lead to a more precise definition of the two centers A and P, and to the formulation of the bipolar geotectonic model in 1969. The evolution of the system of oceanic ridges in the Pacific and anti-Pacific hemispheres demonstrated the breakup of the old lithosphere in the Pacific region (LARSON & CHASE 1972; LARSON & PITMAN 1972; HILDE et al. 1977) and the simultaneous large-scale diverging plate movements within the past 180 Ma in both hemispheres (Figs. 2, 3, 4).

Finally, during the past decade, extensive geophysical research about the distribution of lateral heterogeneities of seismic velocity and density in the Earth's mantle (MASTERS et al. 1982; DZIEWONSKI 1984; WOODHOUSE & DZIEWONSKI 1984, 1989; GIARDINI et al. 1987; TANIMOTO 1990), as well as the interpretation of the geoid (CHASE 1979; CROUGH & JURDY 1981; HAGER 1984), revealed the same Pacific/anti-Pacific hemispherical symmetry as previously found by the geological investigations. The existence of a fundamental geotectonic bipolarity is, thus, founded on independent, observational evidence.

Dynamic Earth

The past three decades of geophysical and geological research brought about a tremendous increase of knowledge of the Earth. In particular, the continuing high tectonic activity of our planet has been clearly demonstrated. The lithosphere, i.e. the

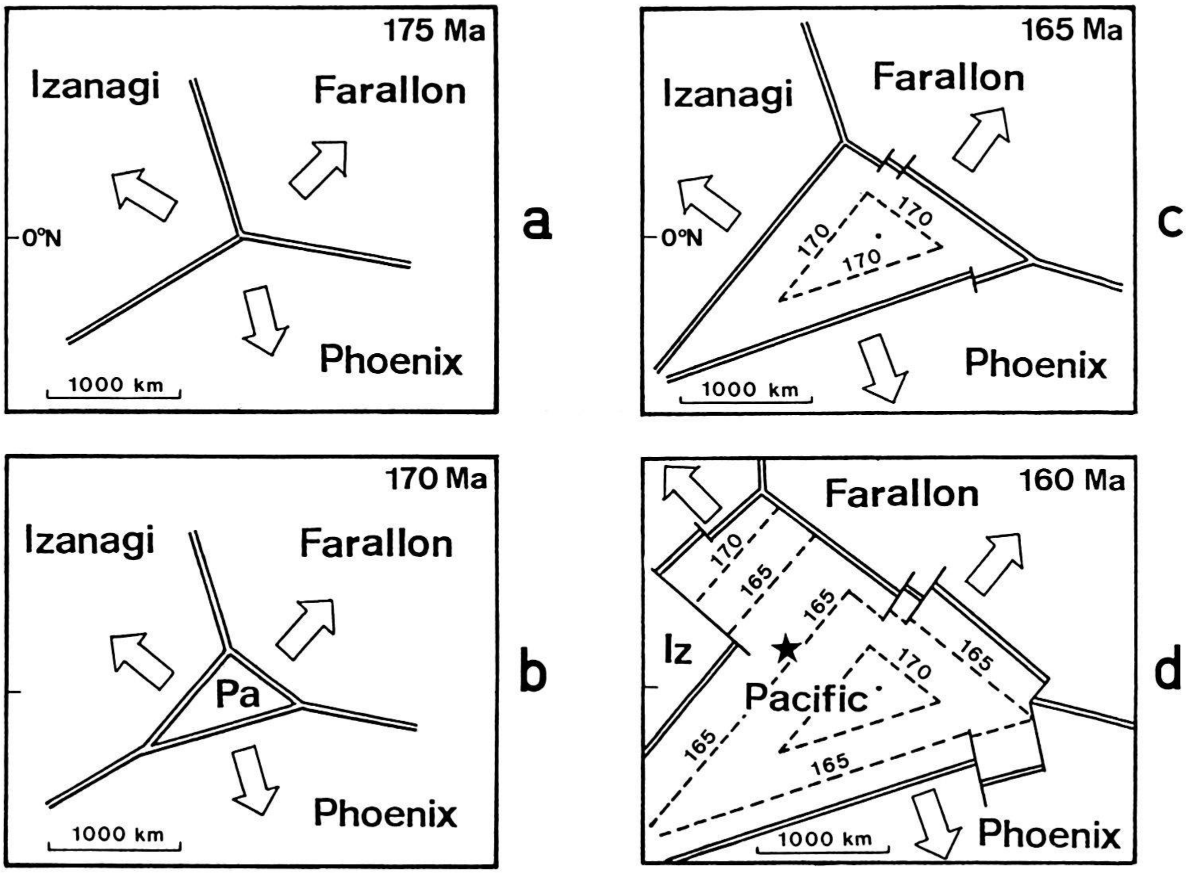

Fig. 2. Origin and growth of the Pacific plate between 175 and 160 Ma, based on the reconstructions by LARSON (1976), HILDE et al. (1977) and RENKIN & SCLATER (1988). Spreading ridges are represented by double lines, fracture zones by single lines. Isochrones on the Pacific plate are represented in 5 Ma intervals by dashed lines according to RENKIN & SCLATER (1988). The Pacific plate (Pa) began to form at about 174 Ma in the center of the Izanagi-Farallon-Phoenix triple junction (a, b). The arrows indicate the movements of the three older plates relative to the Pacific plate. The star (d) marks Site 801 of Leg 129 of the Ocean Drilling Program where, in 1990, Jurassic oceanic crust and sediments (Callovian) have been recovered (LANCELOT & LARSON 1990). The position of the equator is indicated in order to stress the fact that the Pacific plate originated and grew in equatorial paleolatitudes.

outer rigid, about 100 km thick boundary layer, is involved in a continuous circulatory process: Along the active oceanic ridges new oceanic lithosphere is being formed by sea-floor spreading. The plates adjacent to the active ridges increase in size, as the newly formed lithosphere is added to them. At the same time they undergo large-scale horizontal tectonic transport. The young folded mountain belts and island arcs mark the zones of lithospheric convergence. In general, if oceanic lithosphere is involved in the process of lithospheric convergence it is subducted and descends into the mantle, whereas the continental lithosphere remains at the Earth's surface. Growth, tectonic transport and subduction of oceanic lithosphere are manifestations of a large-scale circulation process in the mantle.

There are two types of lithosphere, the oceanic lithosphere which forms the lithosphere in oceanic regions, and the continental lithosphere which includes the continents, the shelves and continental slopes. The division into two types of lithosphere is clearly demonstrated by the hypsographic curve of the Earth. The distribution of elevations is bimodal. The peak near 0.1 km corresponds to the mean elevation of continents, the peak near −4.7 km to the mean depth of the oceans.

Geotectonically, the continental lithosphere behaves quite different from the oceanic lithosphere. Since it is slightly less dense than the oceanic lithosphere and the upper mantle it remains at the Earth's surface, whereas the oceanic lithosphere, after aging and cooling, will be subducted into the mantle, and thus participate directly in the recycling and circulation of mantle material.

Within the past 180 Ma the whole of the oceanic lithosphere underlying the present oceans has been newly formed. This corresponds to a renewal of two thirds of the Earth's lithosphere within a rather short geological period. Within the same period older oceanic lithosphere of the same extent was subducted in the mantle, giving way to its replacement by new oceanic lithosphere.

The mantle represents the thick layer between the crust (the uppermost part of the lithosphere) and the core. It reaches a depth of 2,900 km, and contains the major part of the Earth's mass. The core mantle transition zone, at 2,900 km depth, is a major thermal boundary layer as well as a chemical reaction zone between the regimes of the lower mantle and the outer core (ANDERSON 1989; THOMPSON 1991).

To long sustained loads the mantle behaves as a viscous fluid. The thermal history of the Earth as well as global tectonics are controlled by the fluid-like behavior of the mantle. The flow movements and the resulting convection in the mantle serve at a most effective transport of heat from the interior to the surface of the Earth. Since creation

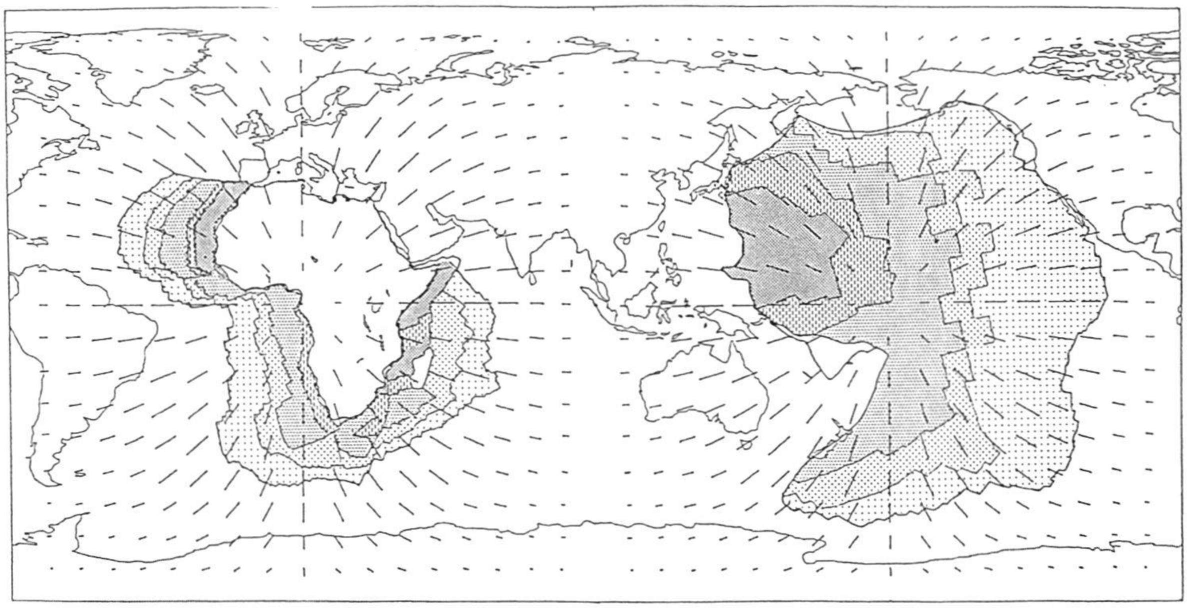

Fig. 3. Concentric and simultaneous growth of the African and Pacific plates. Age of the lithosphere indicated by signature. Lines: Direction of sub-lithospheric flow away from the two upwelling centers toward the GRS equator, according to the bicellular convection model (see Fig. 6, 7). Length proportional to the horizontal component of flow velocity.

and destruction of oceanic lithosphere are regarded as manifestations of large-scale circulation processes in the mantle it may well be assumed that there are mutual interactions between the flow in the upper mantle beneath the lithosphere and the plate movements.

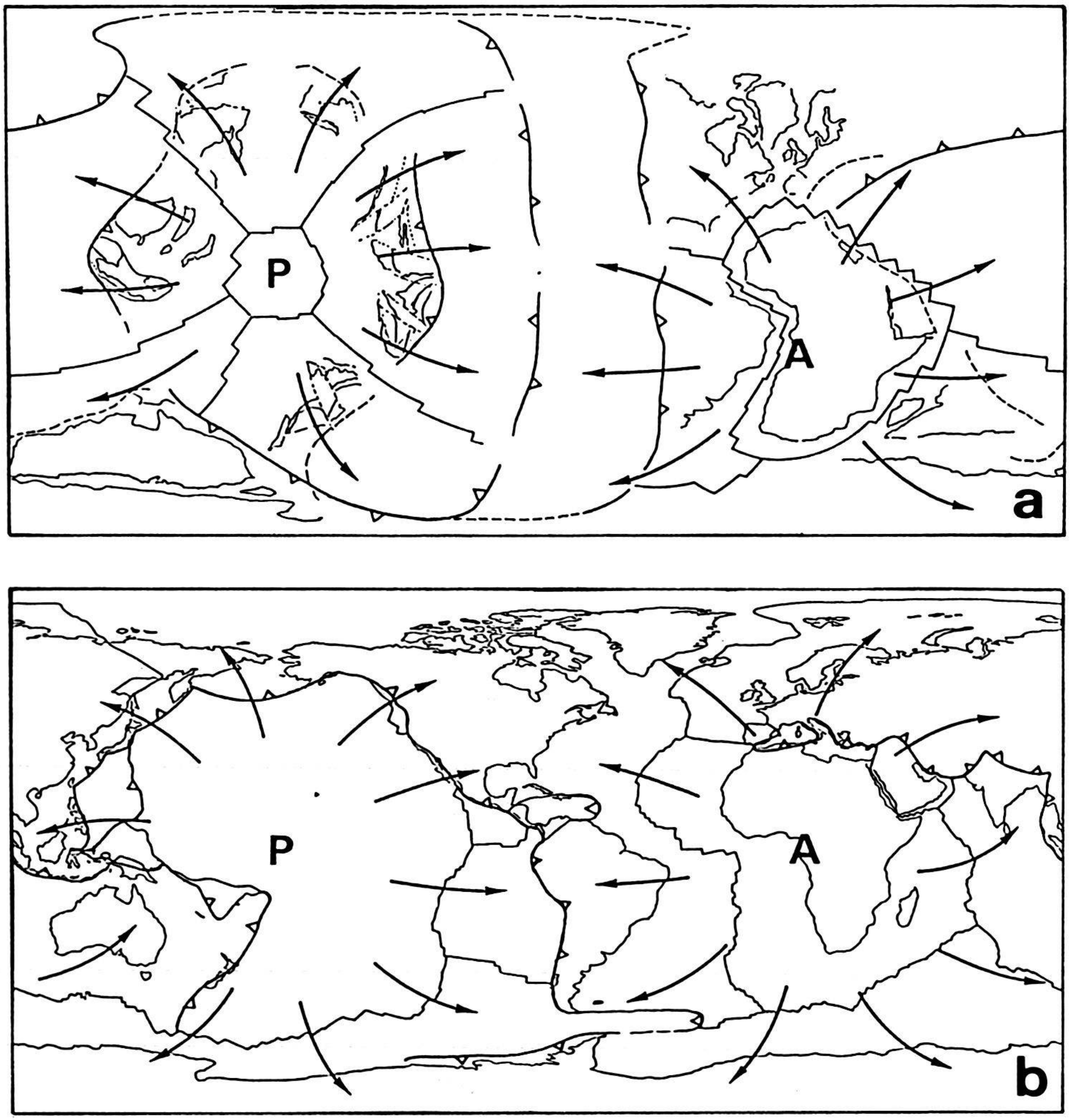

Fig. 4. Geotectonic bipolarity and paleogeographic evolution of the lithosphere in the Pacific and Eurafrican hemispheres. Schematic representation. World maps in cylindrical-equidistant projection. Contour lines of continents and continental fragments are partially indicated. Single lines: divergent and transform boundaries. Lines with barbs: convergent boundaries. (a) Breakup of Gondwana and Pacifica. Stage at about 140 Ma. Diverging movements of plates away from the spreading centers P and A. The Pacific plate originated as a small plate near the equator and is rapidly growing. Center A is moving toward the equator. A North-South trending zone of convergence, subduction, and downwelling in between the two spreading centers is indicated. (b) Present configuration of the Earth's lithosphere.

Drag exerted to the base of the lithosphere is considered to be a major regulating force of large-scale plate motions, although, the strength of coupling between the plates and the flow may be rather weak. Regularities in the global pattern of Mesozoic and Cenozoic plate motions are expected to reflect corresponding regularities in the pattern of large-scale convection in the mantle. A comprehensive knowledge of recent crustal motions, as well as a reconstruction of lithospheric motions on a global scale during the last 200 Ma should, therefore, provide valuable information about the pattern of large-scale, sub-lithospheric flow in the mantle.

The breakup of the lithosphere in the Pacific hemisphere

Large-scale, diverging, horizontal motions of lithospheric plates away from the equatorial Pacific region towards the margins of the Pacific are documented by the evolution of the system of oceanic ridges in the Pacific hemisphere during the last 180 Ma. About 180 Ma ago the lithosphere of the Pacific hemisphere broke into several large pieces, such as the Izanagi plate, the Farallon plate and the Phoenix plate (Fig. 2). As a consequence these plates began to drift radially apart, and in between them a new system of oceanic ridges, connected by a triple junction (LARSON & CHASE 1972; LARSON & PITMAN 1972; HILDE et al. 1977; RENKIN & SCLATER 1988), the Izanagi-Farallon-Phoenix (I-F-P) triple junction, was formed. The I-F-P triple junction was located in the equatorial Pacific region. Soon after the beginning of the breakup of the old lithosphere, a small new plate began to form in the center of the I-F-P triple junction, the Pacific plate (HILDE et al. 1977; HANDSCHUMACHER et al. 1988; SAGER et al. 1988; SHARMAN & RISCH 1988). The magnetic remanent inclination, composition and microfossil content of the Jurassic rocks recovered in 1990 during ODP Leg 129 at site 801 in the Pigafetta basin prove that the Pacific plate was formed at equatorial paleolatitudes (LANCELOT & LARSON 1990). The ODP Leg 129 results are of fundamental importance for the reconstruction of the paleogeographic evolution of the lithosphere in the Pacific hemisphere during the last 170 Ma. They disprove an origin of the Pacific plate at higher, southern latitudes or a derivation from the Antarctic part of Gondwana.

With respect to the Pacific plate the Izanagi and the later Kula plate moved toward the NW and were subducted under Asia and Alaska, the Farallon plate moved toward the NE and was subducted under North America and South America, the Phoenix plate moved toward SE and was subducted under South America and Antarctica. During the same period the Pacific plate was growing from a small plate to its present large size and circular shape (Figs. 3, 4). Notably, the site of origin of the early Pacific plate was located near the geometric "center" of the present Pacific plate. During the growth of the plate the center of the Pacific plate remained in equatorial latitudes; i.e., the growth of the Pacific plate was more or less symmetrical with respect to the equator. The concentric growth pattern of the plate, which for a large part is still preserved, demonstrates continued, large-scale diverging movements of neighbouring plates away from the Pacific plate. In combination with the recent ODP Leg 129 results it is concluded that large-scale diverging horizontal plate movements, away from a center in the equatorial Pacific, were dominating the evolution of the lithosphere in the Pacific hemisphere during the last 180 Ma.

The findings about large-scale, diverging, horizontal motions of plates in the Pacific area, as derived from sea-floor spreading, were independently corroborated by the discovery of "accreted terranes" in the circum-Pacific orogenic belt in North America and in Asia (HOWELL 1985). Accreted terranes or allochthonous terranes are isolated tectonic units which were transported as blocks or microcontinents over large distances from the central and equatorial regions of the Pacific to the borders of the Pacific where, in connection with the subduction of the oceanic lithosphere, they became accreted and integrated as "stranger units" into the mountain belts.

Breakup of the lithosphere in the Eurafrican hemisphere

Simultaneous with the described plate movements in the Pacific hemisphere a comparable, diverging motion of the lithosphere was taking place in the Eurafrican hemisphere. This is documented by the Mesozoic and Cenozoic breakup of Gondwana (Gondwana = southern part of Pangea) and Laurasia (SCOTESE et al. 1988). Relative to the African plate the North American plate moved toward NW, the South American plate toward W, the Antarctic plate toward S, the Australian plate generally toward E, and the Indian plate toward NE. In connection with these large-scale diverging plate motions the Atlantic and Indian oceans were formed. During the same period the African plate was growing to its present size (Figs. 3, 4).

Geotectonic bipolarity, Pacific pole P, African pole A

The parallel evolution of the lithosphere in the Pacific and Eurasian hemispheres during the last 180 Ma, as outlined in the previous sections, reveals a fundamental hemispherical symmetry or bipolarity of global tectonic processes. The bipolarity is defined by two spreading centers P and A in the central Pacific region and in Africa (Fig. 5). The existence of these two spreading centers was first indicated by the results of kinematic analyses of crustal deformation within the Eurasian and circum-Pacific orogenic belts (Fig. 1). Their exact position was derived from the circular arrangement of active oceanic ridges in the eastern Pacific and around Africa. Since the seismicity accurately follows the active ridge segments and transform faults, the distribution of epicenters was used in the definition of the poles (PAVONI 1969, 1971).

Pole P is defined as the pole of a spherical zone containing the epicenters of the Juan de Fuca ridge, the Gorda ridge, the East Pacific rise and the Pacific-Antarctic ridge (Fig. 5). Pole A is the pole of a spherical zone containing the epicenters of the Carlsberg ridge, the Southwest branch of the Indian Ocean ridge, and the Mid-Atlantic ridge up to Gibbs fracture zone. Pole P is located at 170° W/0° N, Pole A at 10° E/0° N. Their position is determined with a precision of ± 3°. The poles are located, within a few degrees, in antipodal position on the equator. This is remarkable, in view of the fact that they are defined independently from each other.

The Geotectonic Reference System (GRS)

Pole P and A define a spherical coordinate system, the Geotectonic Reference System GRS. The position of a point by reference to the GRS is best described by the

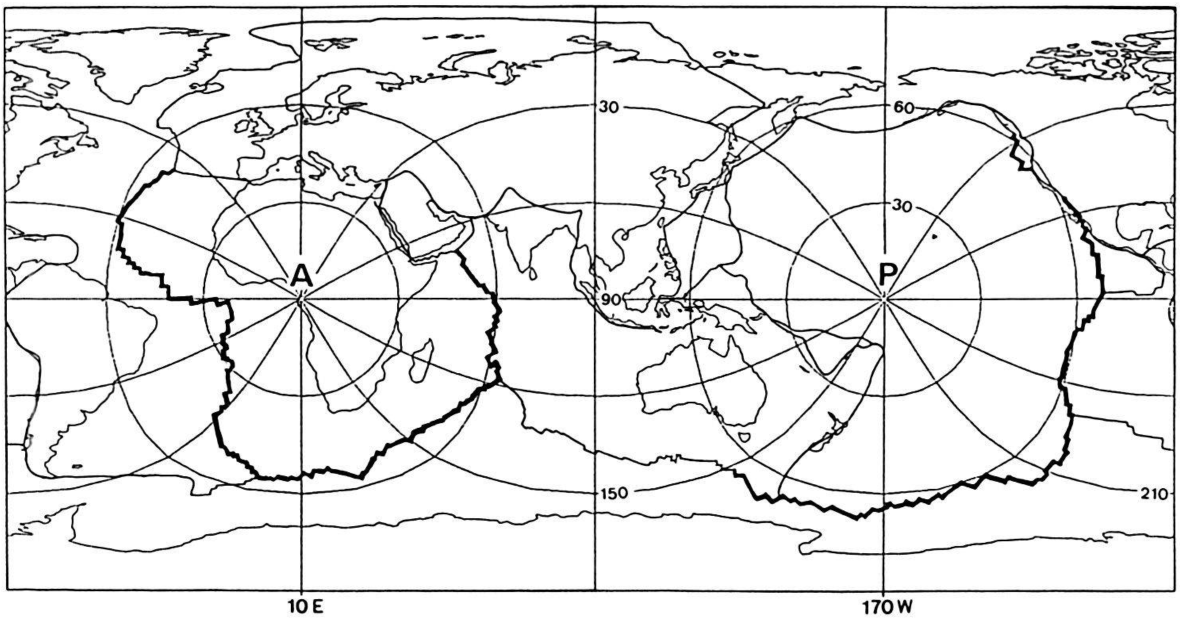

Fig. 5. The Geotectonic Reference System GRS as defined by the Pacific pole P, at 170° E/0° N, and the African pole A, at 10° E/0° N (Pavoni 1969, 1981), and major plate boundaries. World map in cylindrical, equidistant projection. Pacific colatitude θ_P and Pacific longitude λ_P are indicated. P has been defined as the pole of a spherical zone containing the epicenters along the Juan de Fuca Ridge, the Gorda Ridge, the East Pacific Rise, and the Pacific-Antarctic Ridge (heavy line). A has been defined as the pole of a spherical zone containing the epicenters along the Carlsberg Ridge, the Southwest Branch of the Mid-Indian Ridge, and the Mid-Atlantic Ridge between 10 and 40° northern latitude. In the frame of the Geotectonic Reference System the African plate and the Pacific plate are homologous plates.

Pacific coordinates (Fig. 5). Pacific co-latitude θ_P defines the distance of the GRS small circles from the pole P, and Pacific longitude λ_P the distance of the GRS great circles from the meridian through pole P and the North pole. The GRS equator is identical with the 100° E/80° W meridian.

The GRS displays a remarkable relationship with the Cenozoic tectonic deformation picture of the Earth (Pavoni 1970, 1981). Many oceanic ridges, ridge segments, and transform faults trend either GRS latitudinally; i.e., parallel to GRS small circles, such as the East Pacific rise, the Pacific Antarctic ridge, the Carlsberg ridge, the South West Indian Ocean ridge, or GRS longitudinally; i.e., parallel to GRS great circles, such as the South East Indian Ocean ridge, and the Cocos ridge.

To a first-order approximation the GRS great circles indicate the direction of sub-lithospheric flow in the mantle (Figs. 6, 7) as proposed by the bipolar, geotectonic model (Fig. 8). In the case of GRS latitudinal ridges the sub-lithospheric current flows transversely to the trend of the ridge (transverse ridges). In the case of GRS longitudinal ridges the flow moves lengthwise to the trend of the ridge (longitudinal ridges). Also to a first approximation, the GRS great circle trends (Fig. 3, short lines) are similar to the orientation of fast phase velocity axes of Rayleigh waves in the upper mantle (Tanimoto & Anderson 1985; Montagner & Tanimoto 1990).

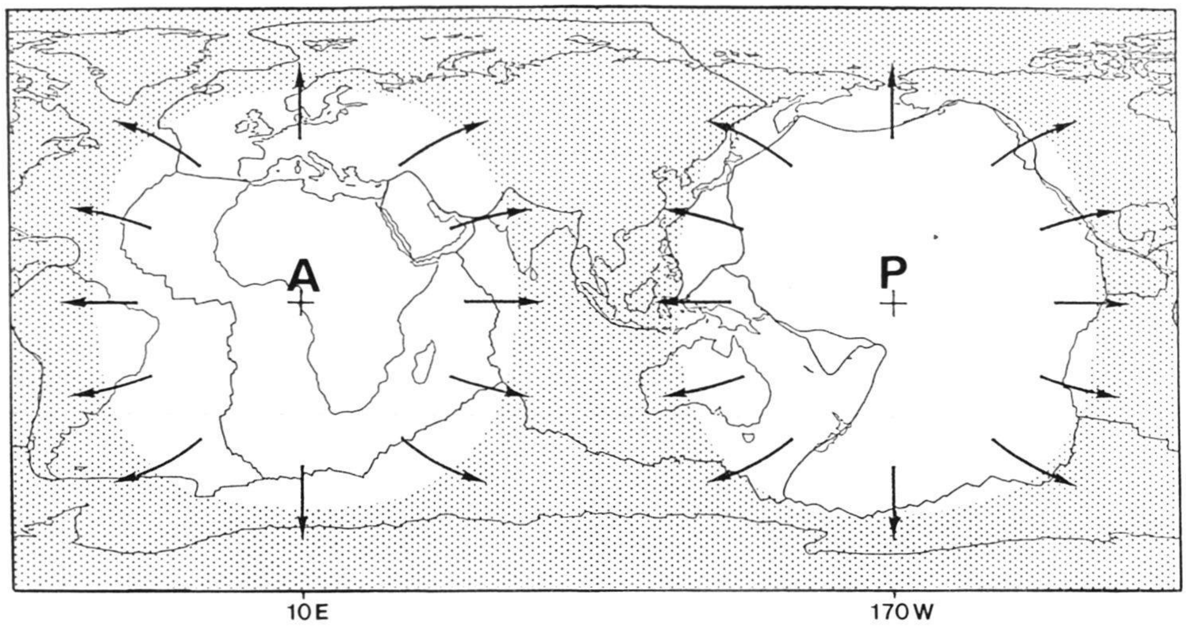

Fig. 6. Schematic representation of the bipolar pattern of sub-lithospheric flow produced by axisymmetric bicellular convection in the mantle (redrawn from Pavoni 1969). Light areas: Diverging lithosphere. Shaded areas: Zone of converging lithosphere (compare with Fig. 7). The poles P and A mark the two major centers of cylindrically upwelling flow in the mantle (see also Fig. 7). They also represent the two major centers of lithospheric divergence.

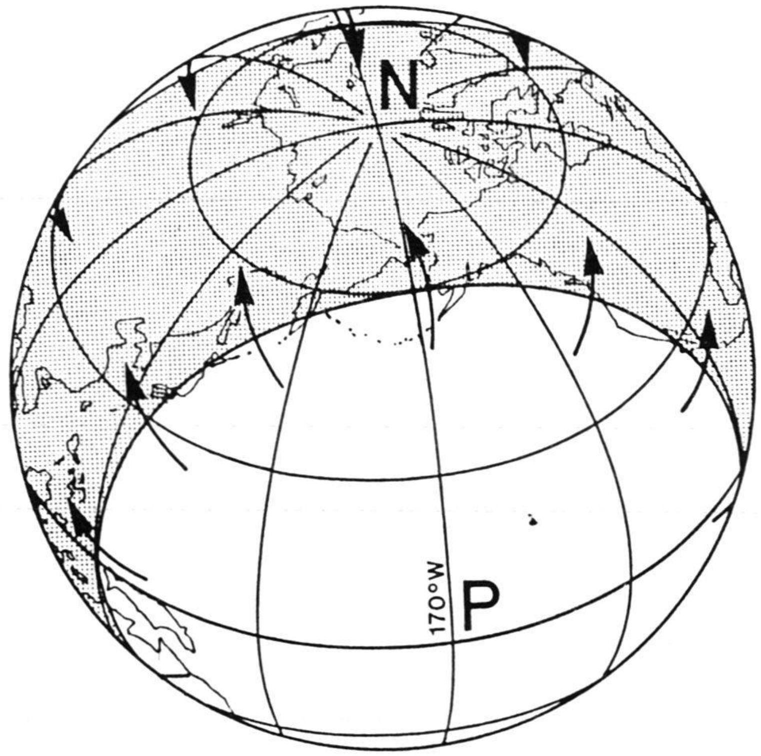

Fig. 7. Idealized representation of the bicellular flow pattern. Orthographic horizontal projection of the Earth, looking at the Pacific hemisphere. P: Pacific pole at 170° W/0° N. Light areas: Diverging lithosphere. Shaded areas: Zone of converging lithosphere (see Fig. 6).

Bicellular convection in the Earth's mantle, the bipolar geotectonic model

The plate motions in the Pacific and Eurafrican hemispheres are regarded as manifestations of a large-scale, bicellular convection in the Earth's mantle with rising currents below both the central Pacific and African plates, P and A marking the centers of upwelling flow. The circulation system is axisymmetric with respect to the axis PA. It consists of two torus-like convection cells, the Pacific convection cell, and the African convection cell (Pavoni 1981, 1988). Underneath the lithosphere the ascending flow is forced to diverge and to move horizontally away from the upwelling centers (Figs. 6, 7, 8). With the beginning of a cycle the overlying lithosphere is gradually weakened and finally torn apart by the ascending and diverging flow in the mantle. The pieces of broken old lithosphere are driven apart. In between them new oceanic lithosphere is formed by sea-floor spreading. In the equatorial zone of the GRS, at about 70° to 90° distance from the upwelling centers, the flow converges and descends into the deeper mantle.

Fig. 8a illustrates the large-scale circulation in a cross section through the Earth along the equator as seen from South. Points P and A mark the position of pole P at 170° W/0° N in the Pacific and pole A at 10° E/0° N in Africa. Since the convection system is axisymmetric with respect to the axis PA, any cross section through the Earth containing the axis PA should represent the same pattern of circulation as shown in Fig. 8a.

Fig. 8b shows the same mantle wide circulation system as in Fig. 8a together with a hypothetical distribution of relative temperatures. Relative warm mantle material

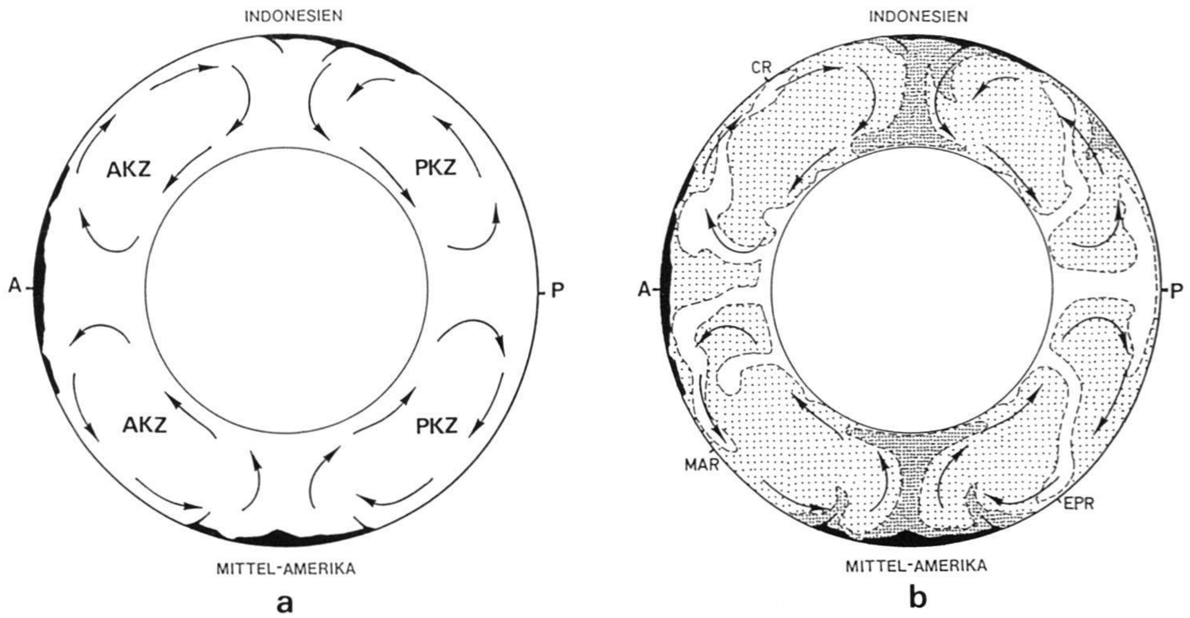

Fig. 8. Cross section through the bicellular convection system in the mantle along the equatorial plane of the Earth, as seen from South (Pavoni 1988). P: Pacific pole at 170° W/0° N. A: African pole at 10° E/0° N. (a) The convection system consisting of two torus-like cells, the Pacific cell (PKZ) and the African cell (AKZ). (b) The circulation system, as in (a), together with a hypothetical distribution of relative temperatures. Dark shading: Relatively cool material. Without shading: Relatively warm material. CR: Carlsberg Ridge. EPR: East Pacific Rise. MAR: Mid-Atlantic Ridge.

(without shading) is ascending at the poles P and A, diverging into horizontal flow underneath the lithosphere. Unidirectional, horizontal flow is shown to occur in the mantle underneath the active oceanic ridges.

In the zone of converging flow, at 70° to 90° distance from the poles P and A, i.e. in the equatorial zone of the GRS, relative cool material (Fig. 8b, dark shading) descends into the deeper mantle. In the zone of converging flow, subduction of cooled oceanic lithosphere is preferentially taking place. Also shown are aperiodic (hot) instabilities in the lower mantle at the core-mantle boundary (Machetel & Yuen 1987; Bercovici et al. 1989; Schubert et al. 1990), which give rise to hot plumes with complicated shapes due to their gradual deformation by the large-scale circulation, and aperiodic (cold) instabilities in the upper mantle at the outer boundary, which produce local sinks and local subduction. The bicellular convection system is not a steady state system. The circulation of mantle material undergoes several phases of evolution, an initial phase, a main phase and a phase of decay. The origin of geotectonic cycles (Pavoni 1981, 1985, 1988) is intimately related with the cycles of circulation.

Unidirectional versus diverging flow in the mantle underneath active oceanic ridges

The concept of unidirectional, horizontal flow in the mantle underneath active oceanic ridges (Fig. 9a) is of fundamental importance in the frame of the proposed bicellular convection model (Figs. 6, 7, 8). It stands in marked contrast to the conventional concept of ascending and diverging flow in the mantle underneath the spreading ridge (Fig. 9b), as illustrated in practically all textbooks of geology and geophysics and review papers (e.g., Anderson 1989, 325; Condie 1989, 188, 352; Cox & Hart 1986, 6, 19, 25; Fowler 1990, 255; Peltier 1989, 250, 766; Wyllie 1988, 4172).

The oceanic ridges are regarded as passive structures and weak zones of the lithosphere (Pavoni 1969). In the case of transverse ridges (see p. 335) the lithosphere is being torn apart due to different drift velocities of the plates adjacent to the ridge (Fig. 9a). The "leading" plate A moves faster than the "trailing" plate B. Magmatic material passively intrudes from the mantle into the thinned lithosphere and crust, and finally extrudes at the surface. Nevertheless, the growth of the plates by sea-floor

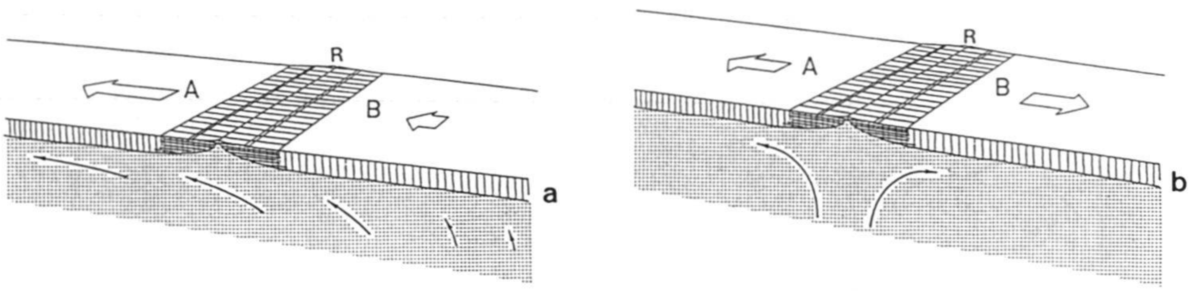

Fig. 9. Sea-floor spreading and sub-lithospheric mantle flow beneath active oceanic ridges, in the case of transverse ridges (redrawn from Pavoni 1969). R: Active central rift. Adjacent hatching: Newly formed oceanic lithosphere. Blank arrows: Velocities of lithospheric plates A and B. (a) Unidirectional flow model: Unidirectional flow with positive horizontal velocity gradient. A: leading plate, B: trailing plate. The whole ridge system is gradually displaced in the direction of flow. (b) Ascending flow, diverging beneath the ridge.

spreading is symmetrical to the ridge axis. As compared with the conventional, diverging flow model, the unidirectional flow model (Fig. 9a) provides a much higher degree of freedom (a) for the actual position of the ridge with respect to the sublithospheric flow, (b) for a lateral displacement of the ridge system, (c) for the development of ridge-ridge transform faults, and (d) for the formation of triple junctions (Pavoni 1969).

A certain asymmetry in the distribution of temperatures in the lithosphere and mantle on both sides of the ridge would be expected in the case of the unidirectional flow model. Looking at Fig. 9a, one would expect relatively higher temperatures in the mantle below the "trailing" plate B than below the "leading" plate A, and thus reduced rates of thickening of oceanic lithosphere on the "trailing" side which is nearer to the main upwelling center and the rising current in the mantle. In a recent study of the global Earth structure by surface waves Tanimoto & Zhang (1990) report of asymmetric thickening of plates about ridges. Reduced phase velocities of Love waves and reduced thicknesses of oceanic lithosphere, as compared to the other side of the ridge, are observed on the East side of the Mid-Atlantic ridge; i.e., on the side near to the African upwelling center, and on the West side of the East Pacific rise; i.e., on the side near to the Pacific upwelling center. The results of Tanimoto & Zhang (1990) represent additional confirmation of the unidirectional flow model. On the other hand the bipolarity model presents a valuable explanation for the asymmetric thickening of plates about certain ridges, as well as for the differences in age-phase velocity curves for the lithospheres of the Pacific, Atlantic and Indian Oceans.

Bipolarity in the structure of the Earth's mantle, geophysical evidence

It is of upmost interest to note that the results of new geophysical investigations about lateral heterogeneities in the structure of the mantle reveal the same Pacific/ African bipolarity as derived from geotectonic considerations (Fig. 10). This information further corroborates the definite interaction between lithospheric movements and mantle dynamics on a global scale.

Fig. 10a represents the degree 2 pattern of lower mantle P-wave velocity heterogeneity after Richards et al. (1988). The GRS poles P and A (Figs. 5, 6) have been added. They are located in the center of the two minima. The lateral heterogeneity of P-wave velocity in the lower mantle exhibits a fundamental bipolarity in exactly the same position as defined by the GRS poles. Reduced P-wave velocities, as shown by the two minima, imply higher temperatures and less dense material relative to the neighbouring mantle. Therefore, upwelling flow in the lower mantle beneath Africa and the central Pacific region is indicated. Upwelling in the upper mantle in the very same regions is assumed by the pattern of sub-lithospheric flow.

The same Pacific/anti-Pacific bipolarity is shown in the degree 2 pattern of the residual geoid (Chase 1979; Crough & Jurdy 1981; Hager 1984; Pavoni 1985). Fig. 10b is redrawn from Richards et al. (1988). GRS poles P and A have been added. They are located near the centers of the two geoid highs. The arrows, redrawn from Pavoni (1969), point away from the two geoid highs toward the geoid low, closely following the gradient of the geoid isolines pattern.

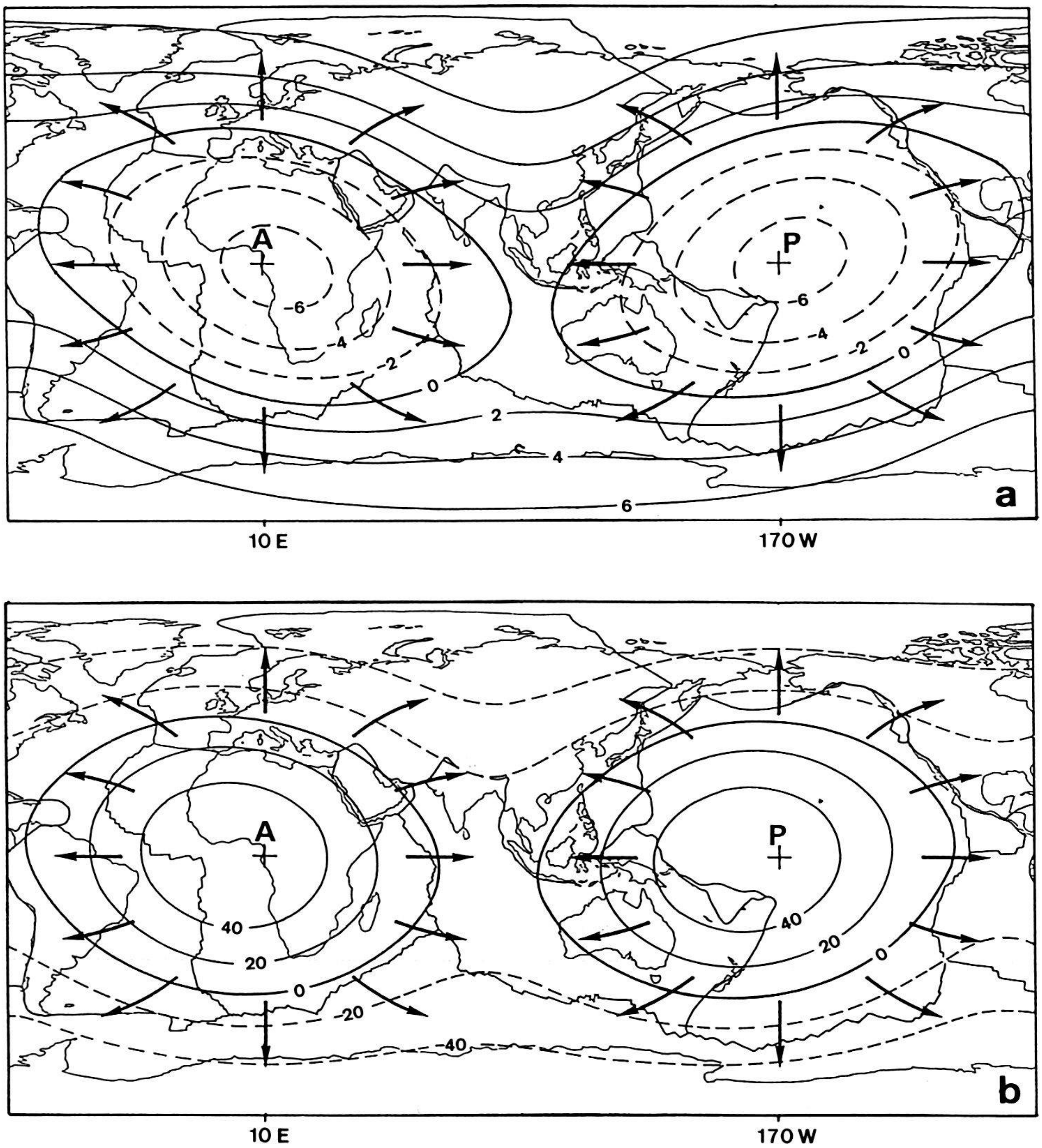

Fig. 10. The fundamental geotectonic bipolarity, geophysical evidence. (a) Heterogeneity of lower mantle P-wave velocity: Degree 2. Contour interval: 2 m/sec. (Richards et al. 1988). The GRS poles P and A have been added. They are located in the center of the two minima. The arrows illustrate the bipolar, sub-lithospheric flow pattern according to the geotectonic bipolarity model as shown in Fig. 6. (b) Residual geoid: Degree 2. Contour interval: 20 m (Richards et al. 1988). The GRS poles P and A are located near the centers of the two geoid highs. The arrows, redrawn from Pavoni (1969), indicate the direction of maximum horizontal velocity of the sub-lithospheric flow according to the geotectonic model (Fig. 6).

Discussion

In the present paper emphasis is given to the reconstruction of plate motions in the Pacific and Eurafrican hemispheres during the last 180 Ma. Of upmost interest is the new insight into the origin and growth of the Pacific plate, resulting from the recovery of Jurassic oceanic crust and sediments of Callovian age in the Pigafetta basin during Leg 129 of the Ocean Drilling Program in 1990. The Pacific plate was formed at equatorial paleolatitudes. During the growth of the plate the center of the Pacific plate remained in equatorial latitudes. Based on the new ODP Leg 129 results and the analyses of Mesozoic magnetic anomalies it may be safely concluded that the large-scale diverging plate motions in the Pacific hemisphere during the last 180 Ma were actually directed away from a common "spreading center" located in an approximately stationary position on the equator. Such a pattern of plate motions conforms with the pattern of sub-lithospheric flow as proposed in the frame of the bipolar geotectonic model (Fig. 6). Plate reconstructions (e.g., Scotese et al. 1988) and the recent ODP Leg 129 results (Lancelot & Larson 1990) place the Pacific spreading center in an approximately antipodal position to the African spreading center as defined by the breakup of Gondwana (Fig. 4a). Together with the results of kinematic analysis of Cenozoic deformation in the Eurasian and circum-Pacific orogenic belts (Fig. 1) they provide the main argument in favour of a Pacific-African geotectonic bipolarity, based on geological observations.

Active oceanic ridges (Fig. 9) represent weak zones of the lithosphere along which the neighbouring plates are torn apart (Pavoni 1969). The intrusion of mantle material and the formation of new lithosphere are a passive consequence of the separation of plates. It is assumed that plates are driven by deep convective flow in the mantle, and active mantle drag force is considered to be the dominant driving force. For the construction of flow patterns in the mantle the choice between the unidirectional flow model (Fig. 9a) and the diverging flow model (Fig. 9b) is crucial. There are a series of arguments to show that the widely accepted diverging flow model is incorrect (Pavoni 1969, 1981). The unidirectional flow model leaves a much higher freedom for the construction of possible patterns of large-scale convection in the mantle. There is no need to directly correlate the distribution of diverging, upwelling flow in the mantle with the distribution of active oceanic ridges. As compared with the diverging flow model, the unidirection flow model allows a lower mode pattern of large-scale circulation in the mantle to be realized. The simple, bicellular pattern of large-scale mantle convection (Figs. 6, 7) is explicitly based on the unidirectional flow model.

The results of new geophysical investigations about mantle structure are reported very briefly and with the main purpose, to demonstrate that the same Pacific/anti-Pacific hemispherical symmetry as previously found by the geological investigations shows up in the distribution of lateral heterogeneities of seismic velocities and densities in the interior of the Earth. For further discussion see Pavoni (1985). Since the flow pattern shown in Fig. 6 represents a degree 2 pattern of sub-lithospheric flow, it is directly compared with the degree 2 pattern of heterogeneity of lower mantle P-wave velocity (Fig. 10a) and the degree 2 pattern of residual geoid anomalies (Fig. 10b). That the same Pacific-African bipolarity is evident in each of the three independent data sets (Figs. 6, 10a, 10b) points to a common origin the of anomalies and the bipolarity. The existence of a fundamental, geotectonic, Pacific-African bipolarity seems to be well established. It may well serve as a geotectonic reference frame.

Should, in fact, the large-scale pattern of mantle convection correspond to the simple, bicellular pattern as proposed in the bipolar, geotectonic model in 1969?

Reduced seismic velocities, indicating less dense and relatively hot material, observed in the lower mantle beneath the central Pacific plate and beneath the African plate, would show up the regions of upwelling in the lower mantle. Relatively high seismic velocities, indicating more dense and relatively cool material, observed in the lower mantle beneath the belt of lithospheric convergence, would mark the regions of downwelling in the lower mantle. These observations are in good general agreement with the mantlewide, bicellular convection proposed on geotectonic considerations.

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